

X-RAY OBSERVATIONS OF THE COMPACT SOURCE IN CTA 1

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ABSTRACT

The point source RX J0007.0+7302, at the center of supernova remnant CTA 1, was studied using the X-Ray Multi-mirror Mission (*XMM-Newton*). The X-ray spectrum of the source is consistent with a neutron star interpretation, and is well described by a power law with the addition of a soft thermal component that may correspond to emission from hot polar cap regions or to cooling emission from a light element atmosphere over the entire star. There is evidence of extended emission on small spatial scales which may correspond to structure in the underlying synchrotron nebula. No pulsations are observed. Extrapolation of the nonthermal spectrum of RX J0007.0+7302 to gamma-ray energies yields a flux consistent with that of EGRET source 3EG J0010+7309, supporting the proposition that there is a gamma-ray emitting pulsar at the center of CTA 1. Observations of the outer regions of CTA 1 with the Advanced Satellite for Cosmology and Astrophysics confirm earlier detections of thermal emission from the remnant and show that the synchrotron nebula extends to the outermost reaches of the SNR.

Subject headings: stars: neutron — stars: individual (RX J0007.0+7302, 3EG J0010+7309) — ISM: individual (CTA 1) — supernova remnants — X-rays: ISM

1. INTRODUCTION

CTA 1 (G119.5+10.2) is one of the class of composite supernova remnants (SNRs) characterized by the presence of pulsar wind nebulae (PWNe) at their centers. The SNR has a large-diameter (~ 107 arcmin) with low X-ray surface brightness (Seward, Schmidt, & Slane 1995) and a partial shell morphology in the radio with an apparent breakout into lower density material in the north (Sieber, Salter, & Mayer 1981). A kinematic distance of 1.4 ± 0.3 kpc has been derived based on the association of an HI shell with the SNR (Pineault et al. 1993).

ROSAT observations of CTA 1 (Seward et al. 1995) reveal a center-filled morphology as well as a faint compact source RX J0007.0+7302 located at the peak of the central brightness distribution (Figure 1). *ASCA* observations show that the diffuse central emission is nonthermal, presumably corresponding to a wind nebula driven by an active neutron star for which RX J0007.0+7302 may be the counterpart (Slane et al. 1997 – hereafter S97). The power law index of this nonthermal emission increases with distance from the center, consistent with synchrotron losses of particles injected from a central source, and there is also weak evidence for a thermal component with $kT \sim 0.2$ keV, presumably corresponding to emission from the SNR shell. No radio counterpart to RX J0007.0+7302 is identified in a list of compact sources by Pineault et al. (1993).

The EGRET source 3EG J0010+7309 (earlier designated 2EG J0008+7307) lies in the direction of CTA 1 (Brazier et al. 1998), and the 95% confidence contour for the location is consistent with the position of RX J0007.0+7302. The two best-established classes of EGRET sources are blazars and pulsars, and the lack of variability in 10 distinct observations of 3EG J0010+7309 (Brazier et al. 1998) argues in favor of the latter interpretation (although Tompkins 1999 presents

mild evidence for variability).

In this paper we report on new X-ray observations of CTA 1 from the *ASCA* and *XMM-Newton* observatories in an effort to better constrain the nature of RX J0007.0+7302 as a candidate pulsar in this SNR. The observations and data reduction are described in Section 2, and the results of the analysis are detailed in Section 3. We conclude with a discussion of new constraints on the nature of RX J0007.0+7302, its relationship to CTA 1, and the extension of its spectrum to γ -ray energies for comparison with 3EG J0010+7309.

2. OBSERVATIONS

2.1. *ASCA* Observations

As an extension of our initial *ASCA* studies that covered only the central portions of CTA 1, we observed the southern shell of the SNR to investigate the spectrum of the nonthermal emission far from the remnant center, and to search for additional evidence of thermal emission from the shell. The 60 ks observation was carried out on 10 February 1997. The approximate field of view of the GIS detectors is illustrated in Figure 1. The SIS detectors were operated in 2-CCD mode, and cover a smaller portion of the SNR with a lower effective exposure. The associated SIS spectra contain relatively fewer counts, and we concentrate on the GIS data exclusively.

We used standard screening procedures to generate a cleaned set of events for each detector, and extracted spectra from the region indicated in Figure 1. Spectra were grouped to contain a minimum of 25 counts in each spectral bin. Background spectra were extracted from the same regions of each detector using data from the available *ASCA* “blank sky” fields. While these fields are at high Galactic latitude, and thus free of diffuse emission from the Galactic Plane, they are adequate for CTA 1 which lies $\sim 10^\circ$ above the Plane. A weighted effective area file was generated for each extended spectral region using the *ascaarf* task in the *ftools* analysis package. The number of counts in each spectrum, after background subtraction, was ~ 3000 . The spectrum from GIS 2 is plotted in Figure 2 along with model fits described below.

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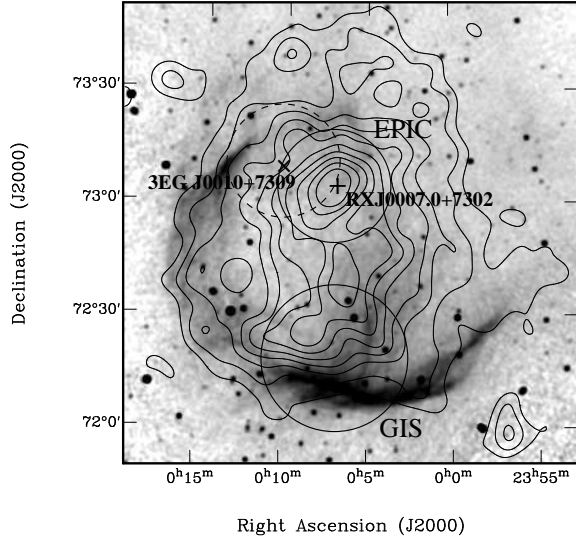


FIG. 1.— Radio image of CTA 1 (from Pineault et al. 1997) with PSPP contours. The location of the ASCA observation described here is indicated by the GIS field of view in the southern portion of the remnant, and the *XMM-Newton* pointing is indicated by the approximate MOS field of view in the center. The position of RX J0007.0+7302 is indicated by a cross. The position of 3EG J0010+7309 is indicated by an X, with the approximate 95% error region shown as a dashed circle. (Note that the actual error region is slightly irregular and overlaps with the X-ray source position.)

2.2. XMM-Newton Observations

CTA 1 was observed for 40 ks with *XMM-Newton* on February 21, 2002 with a pointing direction centered on RX J0007.0+7302. The EPIC cameras were operated in imaging mode, with the medium and thin filters used for the two MOS detectors and the pn detector, respectively. The small window mode with 6 ms time resolution was used for the pn detector in order to search for pulsed emission from the source. Data were filtered to eliminate intervals of high background from soft proton flares, using the Scientific Analysis Software (SAS) package, and events were restricted to the energy range between 100 and 15000 eV. The resulting exposure times were ~ 30 ks (~ 26 ks) for the MOS (pn) detectors, and the observed count rates for RX J0007.0+7302 were 1.3×10^{-2} (2.9×10^{-2}) cnt s^{-1} in the 0.5–10 keV band. The image of RX J0007.0+7302 obtained with the MOS 1 detector is shown as an inset to Figure 4.

Spectra of RX J0007.0+7302 were extracted from each EPIC detector and regrouped to contain a minimum of 25 counts in each bin. Background spectra were taken from regions adjacent to RX J0007.0+7302 in order to include similar contributions from the diffuse emission from the synchrotron nebula. Spectral response (RMF) and effective area (ARF) files were created for each spectrum using the SAS tasks *rmfgen* and *arfgen*. The spectrum from the MOS 1 detector is shown in Figure 3.

3. ANALYSIS

3.1. Spectral Analysis

The ASCA GIS spectra were modeled initially with an absorbed power law spectrum. The fit results in significant residual emission below ~ 1 keV (Figure 2) which is adequately

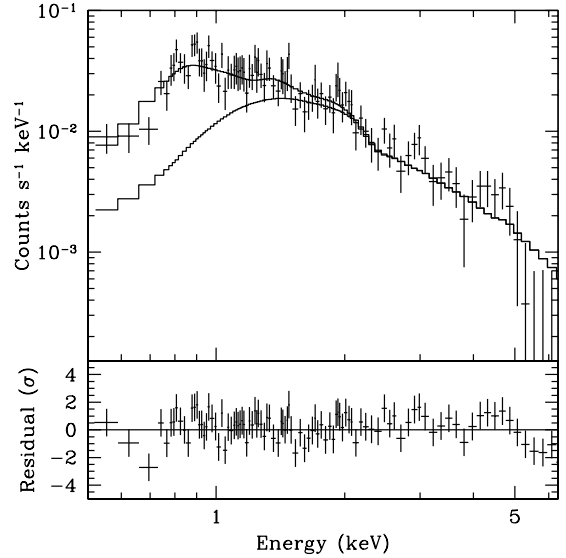


FIG. 2.— ASCA GIS2 spectrum from the southern rim of CTA 1. The top histogram corresponds to the best-fit two component model described in the text. The bottom histogram represents only the power law component.

fit with an additional component for a thermal plasma in collisional ionization equilibrium (Raymond & Smith 1977). While the best-fit column density is consistent with results from earlier ASCA measurements (S97), the uncertainty is large. We thus fix this at the previously determined value of $N_H \sim 2.8 \times 10^{21} \text{ cm}^{-2}$. The best-fit results, summarized in Table 1, yield a spectral index of $2.3^{+0.3}_{-0.4}$ and a plasma temperature of $kT = 0.28^{+0.3}_{-0.08}$ keV. The temperature is consistent with that inferred from earlier ASCA observations.

We first attempted to fit the EPIC spectra of RX J0007.0+7302 using an absorbed power law model. This model provides a good fit, but yields a column density of $\sim 10^{20} \text{ cm}^{-2}$, which is much lower than that for CTA 1. Fixing the absorption at the SNR value yields residual soft emission which is well fit by a blackbody of $kT \sim 130$ eV with an emitting area of radius less than 1 km. The power law index $\Gamma \sim 1.5$ is similar to that of the Crab Pulsar. The best-fit spectral parameters are listed in Table 2. The blackbody flux comprises roughly 20% of the unabsorbed flux from the source. Replacing the blackbody component with a neutron star atmosphere model in a $\sim 10^{12}$ G magnetic field (Pavlov et al. 1995; model kindly provided by Slava Zavlin) reduces the temperature of the thermal component to $T \sim 8 \times 10^5$ K.

3.2. Spatial Analysis

The nominal position of RX J0007.0+7302 derived from the EPIC observations is $\text{RA}_{2000} = 00^{\text{h}}07^{\text{m}}02.2^{\text{s}}$, $\text{Dec}_{2000} = +73^{\circ}03'07''$, with an uncertainty of $\sim 4''$. We find evidence that the source may be slightly extended. In Figure 4 we plot the radial brightness profile extracted from the MOS 1 data, and compare it to that for the point source in G347.3–0.5, obtained from archival *XMM-Newton* data. The point sources were located at the center of their respective fields, and the

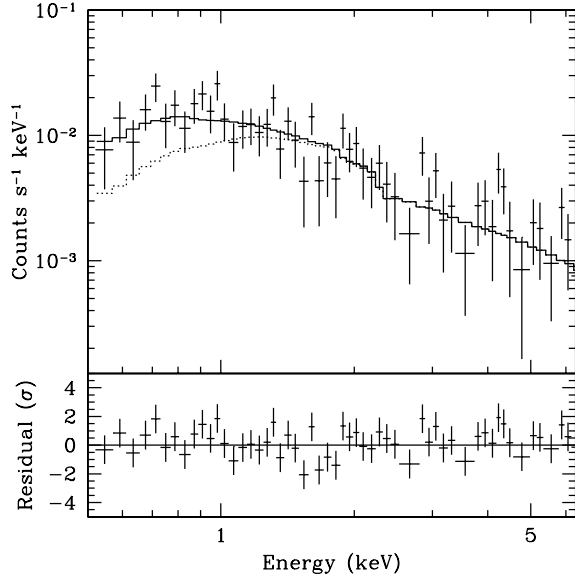


FIG. 3.— *XMM-Newton* pn spectrum of RX J0007.0+7302 in CTA 1. The upper histogram corresponds to the power law plus neutron star atmosphere fit described in the text, while the lower histogram represents only the power law component.

two profiles have been normalized to yield the same number of counts within a 15 arcsec radius. Also plotted is the radial count distribution for the on-axis point spread function (PSF) of the MOS1 telescope in the 0.75–2.25 keV energy range profile, from the *XMM-Newton* Users' Handbook (Issue 2.1), normalized in the same manner. The profile for RX J0007.0+7302 appears to exceed that from the comparison profiles beyond a radius of ~ 10 arcsec. This may be an indication of substructure in the inner portions of the extended nebula. Such structure is now known to be commonplace in PWNe, as dramatically illustrated by high resolution X-ray images of the Crab and Vela pulsars, for example (see Slane 2003). We note that the spectrum for RX J0007.0+7302 is harder than that for the point source in G347.3–0.5 (Lazendic et al. 2003), while the energy-dependent point spread function (PSF) of the *XMM-Newton* mirrors is smaller for higher energies. The apparent extent is thus not an artifact of the telescope PSF.

To further investigate this issue, we extracted spectra from smaller regions surrounding RX J0007.0+7302 and repeated the spectral analysis. We find that the ratio of the blackbody flux to the powerlaw flux increases for the smaller regions, as would be expected if the powerlaw component is extended while the blackbody component is pointlike. This result is not highly significant, however, and observations with higher spatial resolution will be required to confirm such structure in CTA 1. Such observations have recently been carried out with *Chandra* (PI J. Halpern).

3.3. Timing Analysis

We used the EPIC pn data to search for pulsed emission from RX J0007.0+7302. The SAS task *epchain* was used to reprocess events to correct a timing error inherent in some *XMM-Newton* data, and events were then corrected to the so-

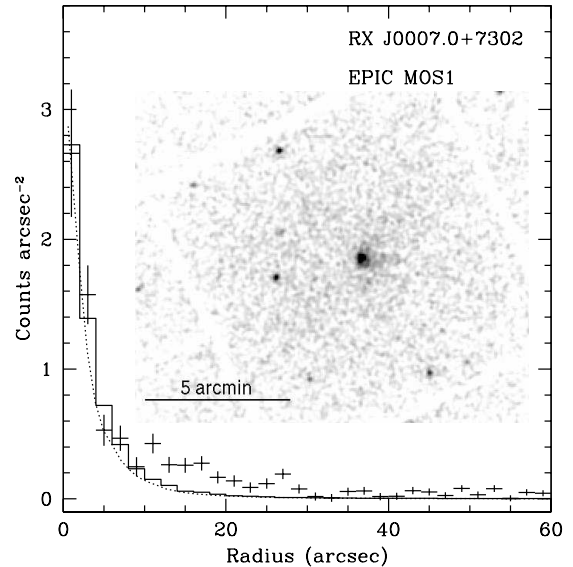


FIG. 4.— *XMM-Newton* MOS 1 brightness profile for RX J0007.0+7302. Also shown is the profile for a similar compact source in the supernova remnant G347.3–0.5 (histogram) as well as the predicted profile for a point source (dashed curve). There appears to be evidence for extended emission from RX J0007.0+7302. The MOS 1 + MOS 2 image is shown as an inset, with a scale bar at the lower left. RX J0007.0+7302 is the brightest source, near the center of the image.

lar system barycenter with the task *barycen*, using the coordinates derived above. A total of 1055 counts in the energy band 0.3–10 keV were extracted from within a radius of 9.6 arcsec, centered on RX J0007.0+7302, with an estimated 483 ± 34 originating from the source (the rest being background events). A Fast-Fourier Transform was applied to the binned light curve using $\sim 8.4 \times 10^6$ bins spanning frequencies up to 83.3 Hz. No significant evidence of pulsations is observed in the resulting power spectrum. The maximum power in the FFT (aside from values corresponding to the ~ 40 ks duration of the observation) was 28.4, from which we derive an upper limit of 61% for the pulsed fraction of a sinusoidal profile in the quoted frequency range (Vaughan et al. 1994).

4. DISCUSSION

Under the Sedov solution (Sedov 1959), assuming a shell-like morphology similar to the radio emission, with a nominal radius of 40 arcmin, and extrapolating our spectral results to the entire SNR, we infer an age of $1.3 \times 10^4 D_{1.4}$ yr (where $D_{1.4}$ is the distance in units of 1.4 kpc), and an ambient density of $1.7 \times 10^{-2} D_{1.4}^{-1/2} \text{ cm}^{-3}$ assuming that the GIS field covers roughly 15% of the emission from the shell. These values, while rather uncertain given the small region observed, are in good agreement with estimates based on earlier *ASCA* observations (S97) and indicate a typical SNR that has evolved in a somewhat low density environment. We note that the density value corresponds to the southern region covered by the *ASCA* observation; the northern region, which extends beyond the nominal radius used here, presumably corresponds to a lower density.

The new *ASCA* observations show that the diffuse synchrotron emission in CTA 1 extends to the outer boundaries of the SNR, at least in the southern shell region. Although the telescope resolution does not allow us to identify the outer ex-

tent with precision, it is clear that the radius of this component is larger than the ~ 18 arcmin ($7.2D_{1.4}$ pc) extent estimated in S97. The PWN is quite large relative to the size of the surrounding shell, although larger PWNe are known (Gaensler, Dickel, & Green 2000). The spectral (photon) index in the outer regions of the nebula may be slightly steeper than the central value of 2.1 ± 0.1 , but not significantly so. This suggests little synchrotron aging of the X-ray emitting electrons, which is indicative of a low magnetic field. This is similar to what is observed for the PWN powered by PSR B1509–58 (Gaensler et al. 2002).

The spectral results derived for RX J0007.0+7302 are consistent with the interpretation that this source is the pulsar that powers the surrounding synchrotron nebula. The luminosity of the power law component from the compact source is $L_x = 4.7 \times 10^{31} d_{1.4}^2 \text{ erg s}^{-1}$. This is low for a pulsar young enough to have an X-ray luminous SNR, but not exceedingly so: PSR B1853+01 is only a factor of two brighter, and is also associated with an observed SNR (W44). The luminosity of the PWN in CTA 1 is $5.6 \times 10^{33} d_{1.4}^2 \text{ erg s}^{-1}$ (S97) which means the point source comprises roughly 1% of the nonthermal emission, a value similar to that for pulsars in 3C 58, G54.1+0.3, and G292.0+1.8. Assuming a spin-down power $\dot{E} \sim 10^3 L_x \approx 5 \times 10^{34} d_{1.4}^2 \text{ erg s}^{-1}$ from the crude correlation derived from X-ray studies of other pulsars (Seward & Wang 1988, Becker & Trümper 1999), RX J0007.0+7302 apparently has sufficient energy to power the nebula. The derived spectral index for RX J0007.0+7302 is similar to that of the Crab Pulsar. If the source is indeed a pulsar with the inferred \dot{E} , this would differ considerably from the empirical relationship between spectral index and spin-down power suggested by Gotthelf (2003).

The position of RX J0007.0+7302 is offset from the geometrical center of the SNR (defined here by the circular portion of the radio shell, ignoring the blowout region in the north). Using the age above, this offset corresponds to a transverse velocity of $\sim 450 \text{ km s}^{-1}$ which is reasonable for a pulsar. We note, however, that the apparent nonuniform density of the surrounding ISM introduces considerable uncertainty in estimating the center of the SNR.

Table 1: Spectral Parameters

	CTA 1 ASCA GIS	RX J0007.0+7302 XMM-Newton EPIC	
	PL + Thermal	PL + BB	PL + NSA
$N_H (\text{cm}^{-2})$		2.8×10^{21} (fixed)	
Γ (photon)	$2.3^{+0.2}_{-0.4}$	1.5 ± 0.2	1.6 ± 0.2
$F_x (\text{erg cm}^{-2} \text{ s}^{-1})^a$	4.8×10^{-12}	2.0×10^{-13}	2.0×10^{-13}
kT (keV)	$0.28^{+0.3}_{-0.08}$	0.136 ± 0.012	0.053 ± 0.004
$F_x (\text{erg cm}^{-2} \text{ s}^{-1})^a$	1.1×10^{-11}	3.3×10^{-14}	3.5×10^{-14}
R (km)		$0.63D_{1.4}$	10 (fixed)
χ^2/dof	437.2/474	117.5/116	112.2/116

a) Unabsorbed flux (0.5–10 keV)

The X-ray spectral index of ~ 1.5 is similar to that for 3EG J0010+7309 in γ -rays (1.6 ± 0.2). We find that extrapolation of the spectrum for RX J0007.0+7302 using $\Gamma = 1.4$ predicts a flux of $4 \times 10^{-7} \text{ photons cm}^{-2} \text{ s}^{-1}$ for $E > 100 \text{ MeV}$, in good agreement with the value measured by EGRET ($4.6 \pm 0.6 \times 10^{-7} \text{ photons cm}^{-2} \text{ s}^{-1}$). Thus, the spectrum of RX J0007.0+7302 is capable of powering the EGRET flux of 3EG J0010+7309 with no spectral break between the two energy bands. This, combined with the fact that there is no

brighter X-ray source in the EGRET error box, and that both RX J0007.0+7302 and 3EG J0010+7309 possess properties indicative of a pulsar, strongly suggests that these sources are one and the same.

The temperature of the blackbody component in the spectrum of RX J0007.0+7302 is too high, and the emitting area is too low, for this to be interpreted as cooling from the surface of a young neutron star (e.g. Kaminker et al. 2002). Rather, this component could be associated with the heating of polar cap regions of the neutron star by instreaming particles accelerated in the magnetosphere (e.g. Pavlov et al. 2000, Zavlin et al. 2002). The lack of observed pulsations from such an emission structure is not worrisome at the upper limit levels derived here. Strong gravitational bending of the emission from near the surface of the NS can easily reduce the pulsed fraction to such levels (e.g. Psaltis, Özel, & DeDeo 2000). More sensitive timing measurements are obviously of considerable interest in an effort to detect pulsations that could potentially secure the identification between RX J0007.0+7302 and 3EG J0010+7309, as well as provide the spindown properties of the pulsar. Deep radio observations have yet to reveal pulsations, with a flux density upper limit of 0.8 mJy at 606 MHz (Lorimer et al. 1998), although recent observations have uncovered much fainter pulsars in the young SNRs G292.0+1.8 (Camilo et al. 2002a) and 3C 58 (Camilo et al. 2002b), both of which are also faint pulsed X-ray sources (Hughes et al. 2003, Murray et al. 2002). Deep X-ray timing observations of RX J0007.0+7302 are currently planned with the *Chandra* HRC (PI S. Murray).

Alternatively, the thermal emission may be the result of cooling from the entire NS surface, viewed through a light element atmosphere. The inferred temperature for such a model, described above, is below that expected for a NS whose age is 10–20 kyr (as estimated for the SNR) assuming cooling by the modified Urca process, but consistent with models in which the direct Urca process becomes active in sufficiently massive stars (Kaminker et al. 2002, Yakovlev et al. 2002). Such models would predict a mass of $\sim 1.44M_\odot$ for RX J0007.0+7302.

5. CONCLUSIONS

We have used *ASCA* and *XMM-Newton* data to study CTA 1 and the apparently associated compact source at its center, RX J0007.0+7302. The diffuse nonthermal emission extending from the central regions of the SNR is consistent with previous interpretations of CTA 1 as a composite SNR containing a large PWN. The faint thermal emission detected along the southern shell is consistent with expectations for a moderate age SNR expanding into a low density environment, as might be encountered at the high Galactic latitude of CTA 1.

The nonthermal nature of the spectrum from RX J0007.0+7302 strongly suggests that this source is a NS with an actively emitting magnetosphere, and the existence of a blackbody-like component in the spectrum indicates the presence of either hot polar caps or cooling of the neutron star surface through an atmosphere. The X-ray luminosity of the source is reasonable for an active pulsar, though rather low for one of such a young age. We do not detect pulsations from the source, and place an upper limit of 61% on the pulsed fraction, which is lower than that for some known X-ray emitting pulsars, but is not overly restrictive on the interpretation of this as the pulsar powering the synchrotron nebula in CTA 1.

We find evidence that the power law component from RX J0007.0+7302 may be extended, suggesting that there

could be inner structure to the known large PWN, and indicating that the pulsar is still supplying energy to the larger nebula. This inner structure could be similar to the jets or toroidal structures that have been recently identified for several pulsars using high-resolution *Chandra* observations.

Finally, we find additional evidence for a connection between RX J0007.0+7302 and the EGRET source 3EG J0010+7309 due to the similarities in the spectra of the two sources. This strongly, though not conclusively, suggests that RX J0007.0+7302 is a pulsar that is emitting both X-rays and γ -rays. More sensitive searches for pulsed emission from

the source, through deeper X-ray observations as well as radio observations, are of considerable interest in an effort to confirm this picture.

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